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Torque ripple minimization of PMBLDC motor using simple boost inverter

V. Krishnakumar[1], N. Madhanakkumar[2], P. Pugazhendiran[3], C. Bharathiraja[4], V. Sriramkumar[5]
[1]Department of Electrical and Electronics Engineering, St. Joseph's College of Engineering, India
[2]Mailam Engineering College, India
[3]Department of Electrical and Electronics Engineering, IFET College of Engineering, India
[4]SRM Institute of Science and Technology, India
[5]Mailam Engineering College, India

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ABSTRACT

This paper proposes the implementation of simple boost circuit incorporated in inverter fed Brushless DC (BLDC) motor drive to boost the performance of torque. BLDC motor becoming subtle because of its performance. But the motor performance is inferior due to the voltage source inverter fed operation of BLDC motor which initiates torque ripple during commutation. Here the usage of Switched Boost Inverter (SBI) which minimizes the storage elements (passive elements), more active element and introduces shoot through mode during commutation as like Z-source inverter. The analyses of three phase switched boost inverter fed BLDC motor drive have been carried out. The performance of torque almost depends on the stator phase current of the motor. In BLDC motor during commutation interval, one phase loss its exact stator phase current hence it instigate ripple on the torque. The proposed method focuses two intentions to reduce the torque ripple. The first intension is to operate the BLDC motor at 180^{o} electrical conduction mode, second intension is to introduce the shoot through interval to boost the dc link voltage so as to maintain the stator phase current control which leads to suppress the torque ripple during commutation. The validation of the proposed SBI based BLDC motor control is demonstrated both by MATLAB/Simulink and Field programmable gate array (FPGA) controller-SPARRTAN III processor. The experimental results of the developed SBI based BLDC motor drive is working over a wide speed range with minimal torque ripple compared to the normal PWM based inverter control.

Corresponding Author:

V. Krishnakumar,
Department of Electrical and Electronics Engineering,
St. Joseph's College of Engineering,
OMR, Chennai-600119, India.
Email: v_krishnakumar@ymail.com

1. INTRODUCTION

In recent days Brushless DC motor becoming popular because of absence of brushes. BLDC motor is used in medical instruments, space, fuel pump, actuators and robotics applications. Normal DC motor has mechanical commutator which was subjected to wear and tear. The introduction of electronic commutator (Six Step Inverter) in BLDC motor made it possible to operate in reliable manner. There are many motors inside the airplane and biomedical instruments is replaced by BLDC motor due to its superior performance like higher dynamic response, higher efficiency and has high torque to weight ratio. This paper presents a SBI which boosts the voltage in the inverter. The boost inverter uses reduced storage elements. This boost inverter is implemented in the BLDC motor drive which reduces the stator current harmonics spectrum.

The digital speed controllers for three phase BLDC motor have been designed to operate in four quadrants. The proposed method confines the power loss and in regenerative mode the energy has been efficiently utilized [1]. The integral variable structure control (IVSC) to reduce the torque ripple in brushless DC motor has been presented. The non ideal trapezoidal back EMF waveshape and conventional current control strategy are the major concern for generation of torque ripple in BLDC motor. The current optimization mechanism has been proposed to reduce the torque ripple [2]. The hysteresis comparator for BLDC motor to achieve sensorless control for automotive fuel pump applications have been designed which senses the three phase terminal voltage and fed to the low pass filter (LPF) to supress the high switching frequency noise. The phase lags of the rotor speed have been denoted by variation in cut off frequency of LPF. The hysteresis comparator has been introduced to compensate the phase lag issues. The phase lag issues have significantly adjusted [3]. The mathematical equation of the cogging torque, unbalanced magnetic force (UMF) and back EMF to the BLDC motor has been derived to estimate the harmonics effect in PM magnetization. The experimental validation of proposed mathematical equations has been tested in hard disc drive. The uneven magnetization of PM caused due to the harmonics of back EMF, cogging torque and UMF has been improved [4]. The Bridgeless cuk converter for BLDC motor drive has been developed. The proposed converter drive operates in discontinuous inductor current mode (DICM) to enhance power factor correction (PFC) and upgrade power quality issues [5]. The novel approach to reduce the torque ripple in BLDC motor drive with SEPIC converter combined with three level neutral-point-clamped inverter has been developed which results better suppression of commutation torque ripple [6].

The torque ripple has been improved only by operating the three phase inverter fed BLDC motor drive in 180° conduction mode instead of frequent 120° conduction mode. The commutation torque ripple mainly happens due to switching of load current from one phase to another phase at every 60° instant. The proposed approach uses dual switching mode technique to enhance the commutation torque ripple of the motor [7]. The new direct torque control for BLDC motor with upgraded reliability has been addressed to limit the torque ripple with the use of three level hysteresis torque controller [8]. The cost effective BLDC drive for water pump application has been designed. The first intend to develop the mapping algorithm to match the torque and speed of the motor in order to achieve better efficiency point. The second intend to develop the cost-effective BLDC motor for widespread numerical analysis technique [9]. The vector approach along with petal shape current trajectory operated PM BLDC motor drive to achieve ripple free torque has been presented. The proposed petal wave current supply improves the torque capability [10]. The torque ripple minimization technique for BLDC motor drive without a DC link capacitor has been developed which uses single switch control strategy, operation is similar to buck converter at any switching state and effective validation has been experimented with a 250 w prototype motor drive, with effective compensation of torque ripple [11]. The analysis of sinusoidal versus square wave current supply for PM BLDC motor drive has been described. The square wave currents supplied to BLDC motor affects the torque performance when the motor operates at high speed and during commutation process the significant torque ripple ascends at both low and high speed ranges [12].

Torque predictive control (TPC) to minimize the torque ripple for PMSM motor drive has been designed which contains mathematical calculations to select the reference voltage vector which control the electromagnetic torque and stator flux with the estimated torque and stator flux errors which further tends to reduce the torque ripple and improved dynamics of the system [13, 14]. Inter turn short circuit fault analysis strategy to interior PMSM for electric vehicle application has been proposed [15]. The regenerative charging control strategy for BLDC motor drive applicable to advanced electric vehicle (EV) has been discussed. The Tagaki-Sugeno (T-S) fuzzy logic control technique has been presented to show the nonlinear dynamics [16]. The PWM technique apt for three phases SBI has been proposed and implemented in digital platform [17]. The established VSI generates output voltage always lesser than the dc input voltage. Hence the introduction of shoot through state in Z-source inverter (ZSI) can boost the inverter output voltage beyond the dc input voltage and triumph over these shortcoming of established VSI. More recently the developed Switched Boost Inverter (SBI) has been extended from single phase to three phases which boosts output voltage beyond the dc input voltage with reduced LC component count [18]. The RPWM technique has been proposed to BLDC motor to enhance the performance of the drive [19]. The space vector PWM approach has been proposed to minimize the torque ripple in BLDC motor [20]. The performance of speed and torque response has been estimated for BLDC motor using fuzzy logic and proportional integral (PI) controller. From the validation, Fuzzy logic controller provides better dynamic performance and limited errors, when subjected to load disturbance [21]. A 21 level multilevel inverter approach with new switching configuration has been proposed for BLDC motor drive. The proposed topology offer satisfied voltage profile with reduced switching devices and reduced torque ripple [22].

The meticulous literature analysis shows that improvement of torque quality in BLDC motor drive is being the motivated topic of many researchers. This paper discusses about the minimization of commutation

torque ripple present in BLDC motor. The three phase SBI connected with BLDC motor drive offers appreciable torque ripple performance. The performance is studied in MATLAB/Simulink simulation platform and compared the results with experimental setup.

2. PROPOSED TOPOLOGY OF THREE PHASE SBI BASED BLDC MOTOR DRIVE

Figure 1 shows the provenience of torque ripple in permanent magnet machines, in which the proposed topology focuses on current commutation events. The proposed three phase switched boost mode incorporated in inverter fed BLDC motor pioneer shoot through mode during commutation interval with minimum passive component.

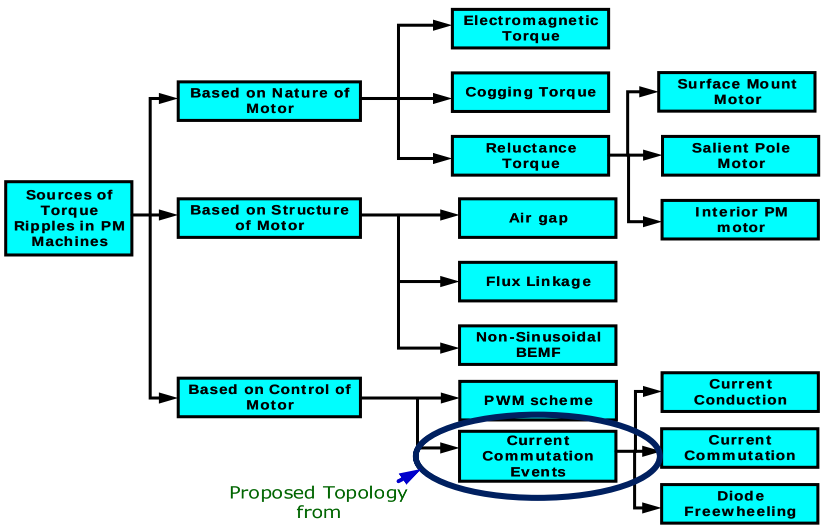


Figure 1. Torque ripple sources in PM machines

Figure 2 shows the three phase SBI based BLDC motor drive. Since the BLDC motor uses rotor position sensor, this is logically ANDed with the switching pattern of Switched boost inverter.

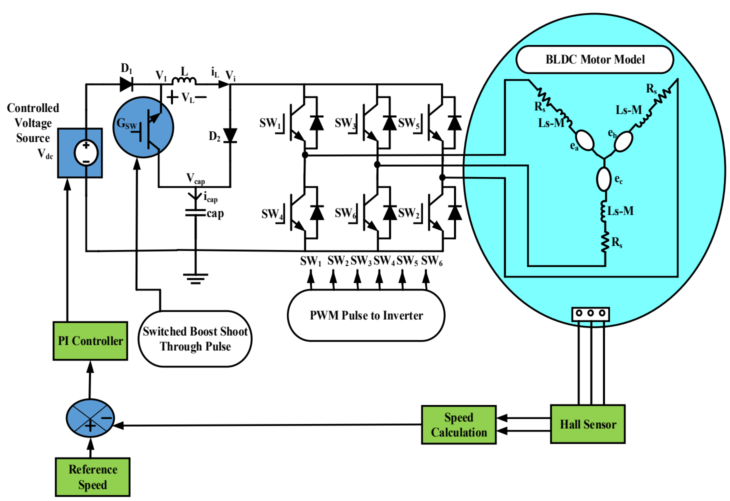
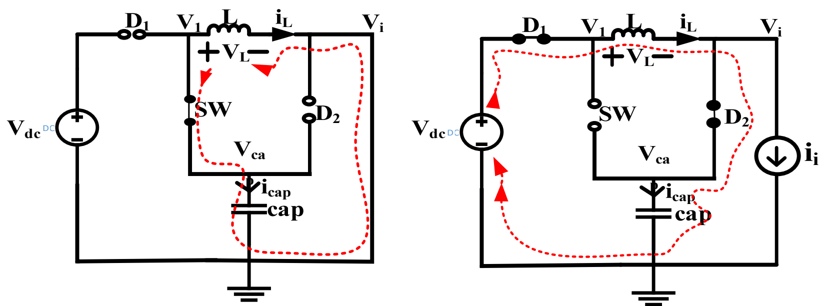


Figure 2. Three phase SBI based PMBLDCM drive



(a) Mode 1 (b) Mode 2

Figure 3. (a) Equivalent circuit of SBI during switch 'SW' ON,
(b) Equivalent circuit of SBI during switch 'SW' OFF

The steady state operation of the boost inverter in mode 1 explains the inverter is in shoot through state for duration t_{on} in a switching cycle T_S. The switch SW is also turned on during this interval. In this mode the diodes $D_1$and D_2 are reverse biased (as $V_{Cap}>V_{dc}$), and the capacitor C charges the inductor L through switch SW and the inverter bridge which is shown in Figure 3a. The mathematical equations governed by the inverter during mode 1 are given in (1).

$$V_L = V_{cap}\,; i_{cap} = -i_L\,; V_i = 0 \tag{1}$$

Figure 3b represents the equivalent circuit of SBI during switch 'SW' in OFF duration. During this duration, the switch SW is turned off and diode D_1 and D_2 are forward biased to offer path for the inductor current i_L. The mathematical equations governed by the inverter during mode 2 are given in (2).

$$V_L = V_{dc} - V_{cap}\,;\ i_{cap} = i_L - i_1\,; V_i = V_{cap} \tag{2}$$

3. PWM CONTROL STRATEGY OF THREE-PHASE SBI

The Switching pattern for (GS, GS1, GS3, GS5, GS4, GS6, GS2) of the SBI has been explained in the Figure 3 it is not possible to directly adopt the PWM control strategy of VSI. The SBI uses extra switch 'SW' along with the six step three phase inverter. The introduction of shoot through state in SBI boosts the output voltage of the inverter. The switch 'SW' should be harmonized with the shoot-through state of the inverter. In Figure 4 V_{tri} is the carrier signal with peak value of $V_{p.}$ M is Modulation index, D is duty ratio of shoot through state and f_s is the switching frequency of switched boost inverter. Table 1 gives details about the generation of gate pulses for three phase SBI. Normally BLDC motor can be operated in 180° and 120° mode of operation. Here the SBI is operated in 180° mode which means at any instant three switches are in conduction. During these instant two switches current enters to conduction and the third phase leaves to commutation (due to the loss of exact phase current control). Hence the possibility of torque ripple in BLDC motor tends to affect the performance of motor. At this instant shoot through region has been introduced to retain the third phase current in raising amplitude.

Table 1. Switching pattern for switches S_1, S_3, S_5, S_4, S_6, S_2

Mode No.	Duration	Condition for gate control signal to be High		
		Gs1	Gs3	Gs4
1	0° - 90°	Vma>Vtri	Vmb>Vtri>VST	Vmc>Vtri
2	90° - 210°	Vma>Vtri	Vmb>Vtri	Vmc>Vtri>VST
3	210° - 330°	Vma>Vtri>VST	Vmb>Vtri	Vmc>Vtri
4	330° - 360°	Vma>Vtri	Vmb>Vtri>VST	Vmc>Vtri
Mode No.	Duration	Condition for gate control signal to be High		
		Gs4	Gs6	Gs2
1	0° - 30°	Vma<Vtri	Vmb<VST	Vmc<Vtri<-VST
2	30° - 150°	Vma<Vtri<-VST	Vmb<Vtri	Vmc<Vtri
3	150° - 270°	Vma<Vtri	Vmb<Vtri<-VST	Vmc<Vtri
4	270° - 360°	Vma<Vtri	Vmb<Vtri	Vmc<Vtri<-VST

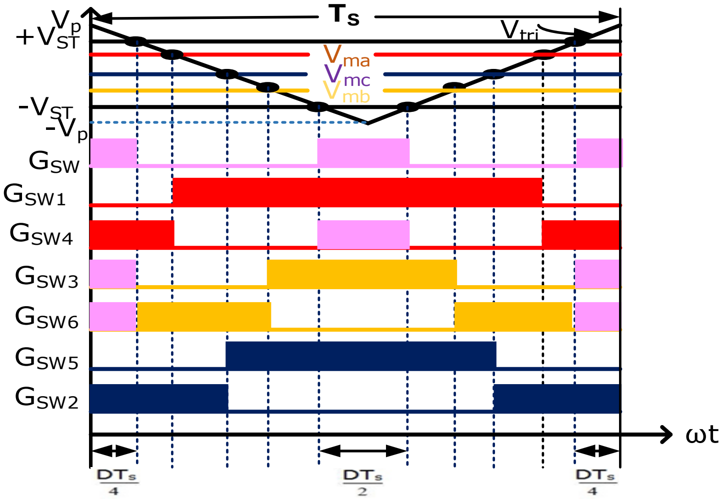


Figure 4. Switching pattern of SBI

4. CURRENT BEHAVIOR DURING SWITCHING USING TRADITIONAL CONTROL

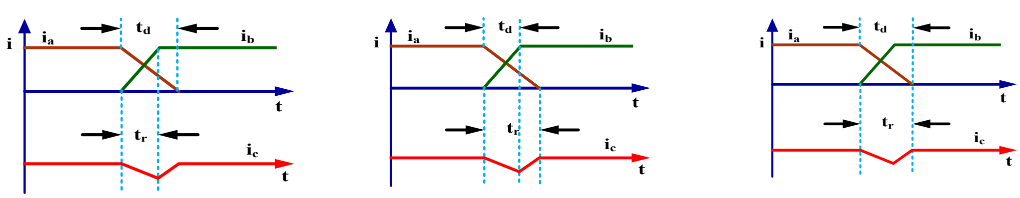
The behavior of the current with different speeds is shown in Figure 5. There are three conclusions that can be drawn:

(1) If Vdc > 2Em, then td > tr, and the torque remains rising during commutation. The phase currents are shown in Figure 5(a).

(2) If Vdc < 2Em, then td < tr, and the torque remains declining during commutation. The currents in the three phases are shown in Figure 5(b).

(3) If Vdc = 2Em, then td = tr, and the torque is constant during commutation, which is the ideal case, where no torque ripple results, which is shown in Figure 5(c).

Considering these relation, this paper proposes a modified circuit topology, which standardizes the dc-link voltage remains to 2 Em throughout the commutation interval. After proper validation, the current increasing and dropping speeds became equal; hence the torque ripple is suppressed.



(a) $V_{dc} > 2\ E_m$, $t_d > t_r$ (b) $V_{dc} > 2E_m$, $t_d < t_r$ (c) $V_{dc} = 2E_m$, $t_d = t_r$

Figure 5 Current behaviors during switching

The time to reach for i_a to become extinct from the primary value is expressed in

$$t_d = \frac{3LI_m}{V_{dc}+E_m} \tag{3}$$

Where V_{dc} is the dc-link voltage.
The time to reach for i_b to increase from 0 to I_m is

$$t_r = \frac{3LI_m}{(V_{dc}-E_m)} \tag{4}$$

5. SIMULATION RESULT

To appraise the utilization of the proposed method, the SBI based BLDC motor drive shown in Figure 2 has been simulated using MATLAB/Simulink. The specification of the BLDC motor used for simulation has been given in Table 2. The torque and stator current waveforms of the simulated BLDC motor drive system using traditional PWM control method at 3000 rpm and load torque of 2 NM are shown in Figure 6a and 6b. Enlarged view of stator current for proposed SBI fed BLDC motor drive is shown in Figure 7. Torque response of proposed SBI fed BLDC motor drive is shown in Figure 8. Stepped input torque response of proposed SBI fed BLDC motor drive is shown in Figure 9. Speed response of proposed SBI fed BLDC motor for different speed ranges i) 750 rpm ii) 3000 rpm is shown in Figure 10. The percentage torque ripple for the traditional control is 50%. The proposed SBI based BLDC motor drive was simulated, and the torque and stator current waveforms of the simulated results are shown in Figure 6c and 6d. The percentage torque ripple for the proposed method is 7%.

Table 2. Motor specifications

Parameters	Values
Stator phase resistance, Rs	2.875 mΩ
Stator phase inductance, Ls	850 µH
Pole pairs	4
DC supply voltage	100V DC
Current limit threshold	20A
DC Bus Capacitance C1 and C2	200 Mf
Inertia, viscous damping, static friction constants	0.8e-3J (kg.m2),1e-3 F(N.m.s)

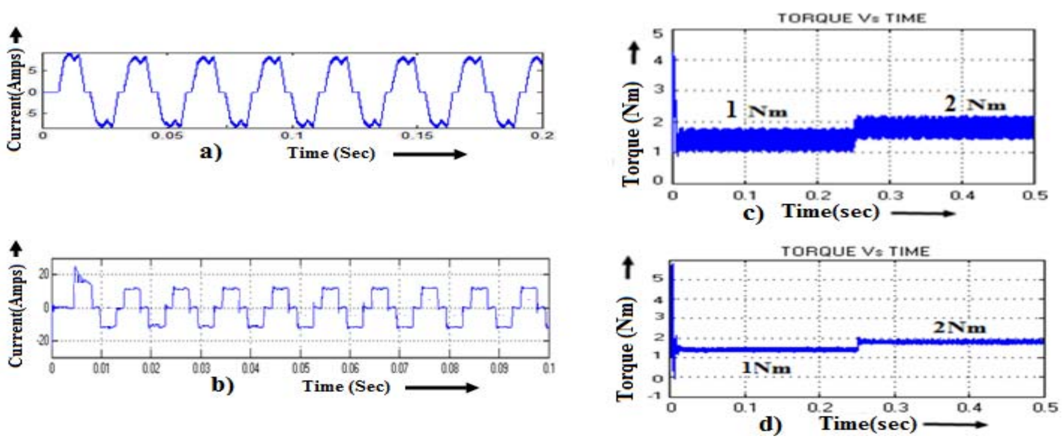


Figure 6. Simulation result of stator phase current and torque, (a) Current waveform from the existing control at 3000 rpm and step torque of 2 Nm; (b) Current waveform from the proposed SBI topology at 3000 rpm and step torque of 2 Nm; (c) Torque waveform from the existing control at 3000 rpm and step torque 2 Nm; (d) Torque waveform from the proposed SBI topology at 3000 rpm and step torque 2 Nm

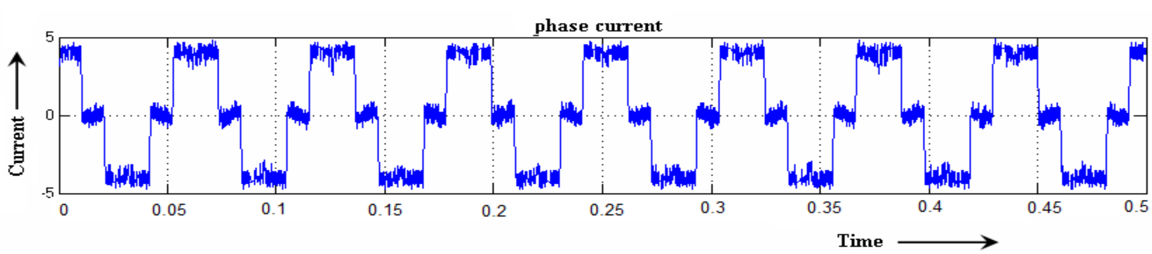


Figure 7. Enlarged view of stator current for proposed SBI fed BLDC motor drive

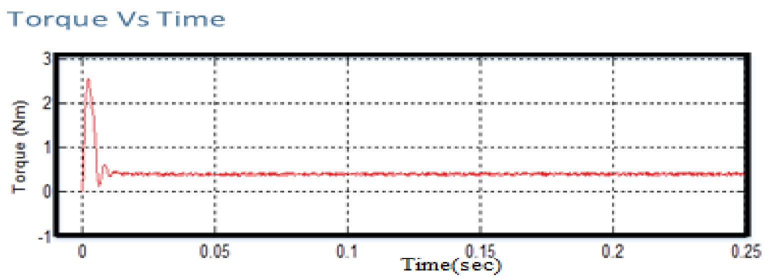


Figure 8. Torque response of proposed SBI fed BLDC motor drive

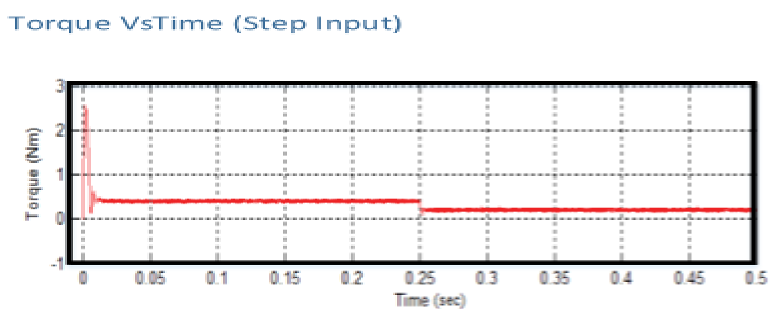


Figure 9. Stepped input torque response of proposed SBI fed BLDC motor drive

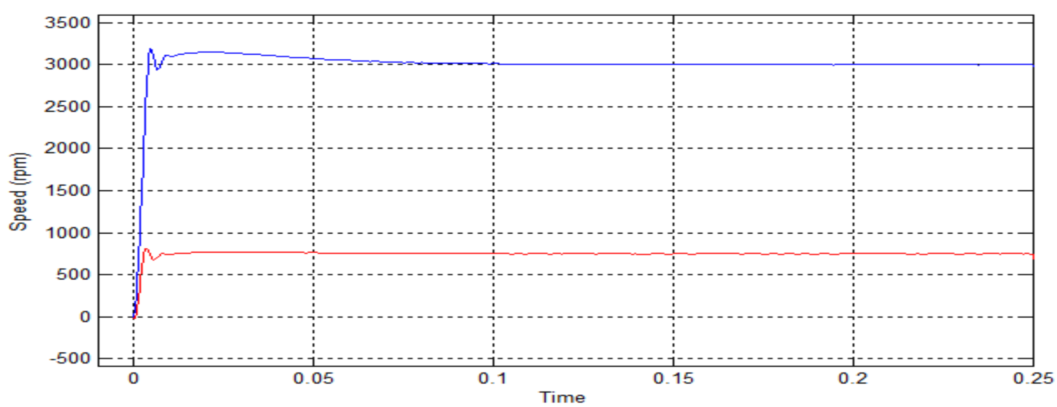


Figure 10. Speed response of proposed SBI fed BLDC motor for different speed ranges (i) 750 rpm; (ii) 3000 rpm.

6. EXPERIMENTAL RESULT

To validate the proposed SBI based BLDC motor performance, a Xilinx Spartan-III 3AN-XC3S400controller is used. MATLAB-Xilinx System Generator tool is used for the implementation. The generated MATLAB-Simulink code is rehabilitated to bit file to access the FPGA board. In order to verify the proposed torque ripple limit strategy, the FPGA controller is programmed in processing unit and controlling unit.

The hall signal from the respective sensors and switching pattern of SBI are logically multiplied using AND gate to generate the corresponding switching pulse for three phase SBI in order to achieve better torque response during commutation interval.

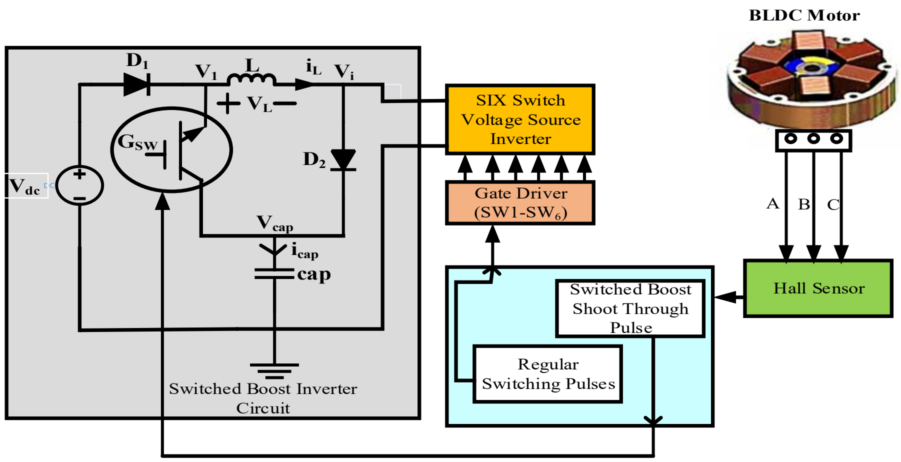
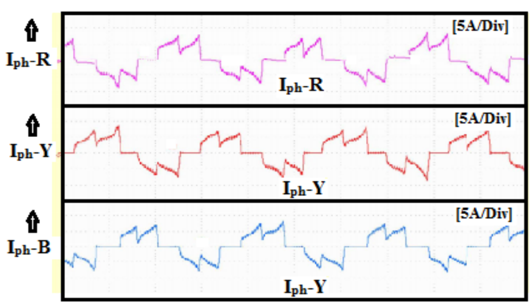


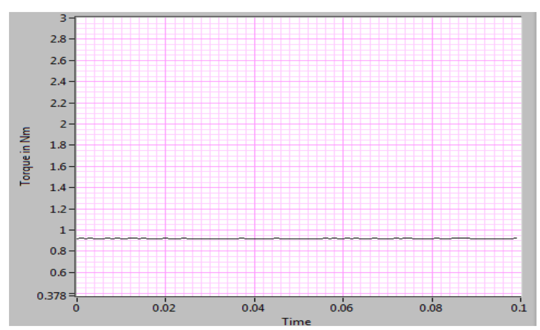
Figure 11 Experimental validation of SBI based BLDC motor drive

The effectiveness and viability of the proposed method has been validated by using real time experiments. The specification of BLDC motor is summarized in Table 2. The experimental set up of the controller used to generate the gate control pulses and BLDC motor are shown in Figure 11. The position of the rotor is sensed using Hall Effect sensors. The Switched boost circuit combined with three phase VSI are operated between 10 to 50 kHz respectively. The experimental and simulation results evident the close match of proposed SBI based BLDC motor drive. Figure 12 a and b represents the phase current response of proposed SBI topology with torque of 0.9 Nm. Figure 12 b. represents the torque response of proposed SBI topology of torque 0.9 Nm. The experimental result validates the torque ripple is reduced in the proposed SBI based BLDC motor drive and can capable to operate over a wide speed range. Figure 13 validates the essence of torque ripple minimization using proposed SBI based BLDC motor drive versus the other drive systems applicable from the literature. The torque ripple calculation of proposed SBI based BLDC motor is given below.

$$\text{Torque ripple} = \frac{T_{max} - T_{min}}{T_{average}} = \frac{0.966 - 0.911}{0.88} = 7\%$$



(a) Three phase current response of proposed SBI topology with torque of 0.9 Nm



(b) Torque response of proposed SBI topology of torque 0.9 Nm

Figure 12. Experimental results of Stator phase current and torque

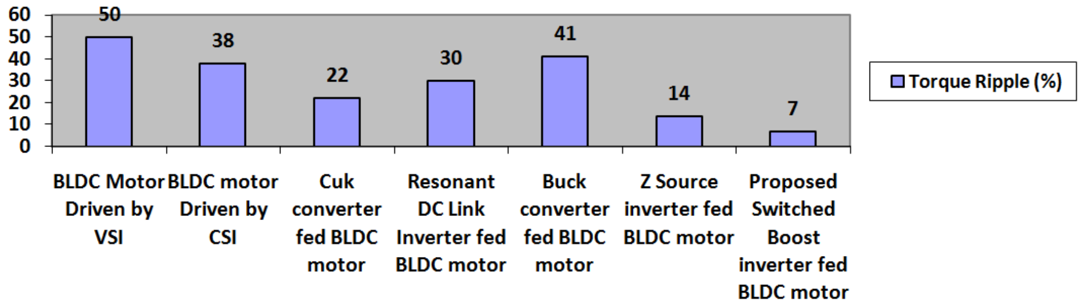


Figure 13 Various drive system versus torque ripple percentage

7. CONCLUSION

The SBI based BLDC motor is proposed that efficiently curtail the commutation torque ripple. The boost circuit has been connected to three phase inverter to regulate the dc link voltage and to curb the commutation torque ripple during switching (commutation interval). To validate the viability of the proposed system, the simulation and hardware setup were performed. Thus the results of the proposed system can effectively minimize the commutation torque ripple which in turn effectively used in medical laboratory applications. The comparison of torque ripple percentage with various drive system is performed, the SBI results better torque ripple minimization with reduced passive components than the other drive systems.

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